

# New particles from Belle

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**Abstract.** I report recent results on hidden charm spectroscopy from Belle. These include: observation of a near-threshold enhancement in the  $\omega J/\psi$  invariant mass distribution for exclusive  $B \rightarrow K\omega J/\psi$  decays; evidence for the decay  $X(3872) \rightarrow \pi^+\pi^-\pi^0 J/\psi$ , where the  $\pi^+\pi^-\pi^0$  invariant mass distribution has a strong peak between 750 MeV and the kinematic limit of 775 MeV, suggesting that the process is dominated by the sub-threshold decay  $X \rightarrow \omega J/\psi$ ; and the observation of a peak near 3940 MeV in the  $J/\psi$  recoil mass spectrum for the inclusive continuum process  $e^+e^- \rightarrow J/\psi X$ . The results are based on a study of a  $287 \text{ fb}^{-1}$  sample  $e^+e^-$  annihilation data collected at center-of-mass energies around the  $\Upsilon(4S)$  in the Belle detector at the KEKB collider.

## 1. Introduction

The recent surge in activity in hadron spectroscopy and, I suppose, the main motivation for the formation of the Topical Group on Hadron Physics, is the result of renewed interest in a rather old question: *are there hadronic states with a more complex structure than the simple  $q\bar{q}$  mesons and  $qqq$  baryons of the original quark model?* This revival of interest has been driven by experimental reports of pentaquarks [1], the narrow  $D_{sJ}$  states [2, 3], and the  $X(3872)$  [4].

In spite of considerable theoretical and experimental effort, the existence of non- $q\bar{q}$  mesons and/or non- $qqq$  baryons remains an open question. While the identification of a strangeness=+1 (or charm=-1) baryon would be definitive evidence for a non- $qqq$  baryon, the experimental situation regarding the existence of such states remains unsettled (and a major topic of discussion at this meeting [5]). On the other hand, while the  $D_{sJ}$  and  $X(3872)$  are experimentally well established, the theoretical interpretation is not so clear. The  $D_{sJ}$  states could be standard  $P$ -wave  $c\bar{s}$  states and their narrowness is only surprising because the relativistic potential model calculations that predicted them to be heavier (and above  $DK$  threshold) are wrong [6]. Some theorists, including our opening speaker [7], remain hopeful that a  $c\bar{c}$  charmonium assignment can be found for the  $X(3872)$ .

To sort this all out, I think that the so-called hidden charm mesons can and will play a decisive role for reasons that include:

- the theory for these systems is well founded (and recently blessed by this year's Nobel Prize Committee) and has fewest ambiguities;
- the experimental signatures tend to be clean;
- $c\bar{c}$  meson states below open-charm threshold are narrow and do not overlap; and

- lots of non- $c\bar{c}$ -type mesons have been conjectured, including  $D\bar{D}^*$  molecules [8] and  $c\bar{c}$ -*gluon* hybrids [9].

Although the Belle detector [10] is specialized to studies of CP violation in  $B$  meson decays, it has proven to be a useful device for studying particles containing  $c\bar{c}$  pairs. Belle detects  $c\bar{c}$  systems produced via weak decays of  $b$  quarks—the  $b \rightarrow c\bar{c}s$  process is a dominant  $b$ -quark decay mode—and the continuum production process  $e^+e^- \rightarrow c\bar{c}c\bar{c}$ , which has been found to be surprisingly large. The KEKB asymmetric energy  $e^+e^-$  collider [11] operates at a center-of-mass (cms) energy corresponding to the  $\Upsilon(4S)$  resonance and routinely delivers luminosities that are in excess of  $10^{34}\text{cm}^{-2}\text{s}^{-1}$ , thereby providing Belle with a huge data sample that contains about 300 million  $B\bar{B}$  meson pair events and over one billion  $e^+e^- \rightarrow q\bar{q}$  continuum annihilation events.

Belle results in the hidden charm meson sector include first observations of:

- the  $\eta'_c$  via the sequence  $B \rightarrow K\eta'_c$ ,  $\eta'_c \rightarrow K_S K\pi$  [12];
- anomalously large cross sections for the exclusive process  $e^+e^- \rightarrow J/\psi\eta_c$  and the inclusive process  $e^+e^- \rightarrow J/\psi(c\bar{c})$  [13];
- the  $X(3872)$  meson [4];
- a near-threshold  $\omega J/\psi$  mass enhancement in exclusive  $B \rightarrow K\omega J/\psi$  decays [14]; and
- a peak at 3940 MeV in the  $J/\psi$  recoil mass spectrum in the inclusive  $e^+e^- \rightarrow J/\psi X$  process [15].

In this talk I will discuss the last two items as well as recent results on properties of the  $X(3872)$ . I will not have time to cover any of the many other Belle results on hadron spectroscopy, such as our many interesting results on charmed baryon spectroscopy [16],  $D^{**}$  [17] and  $D_{sJ}$  mesons [3] and two-photon physics [18]. In addition, I will not have time to report on Belle's lack of observation of pentaquarks [19] or the  $D_{sJ}(2632)$  [20]. All unpublished numbers reported here are preliminary.

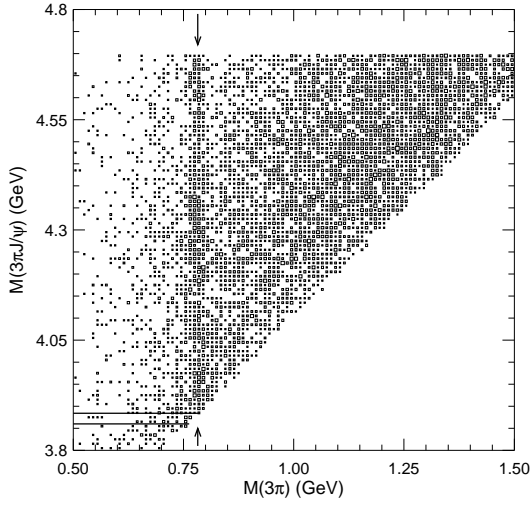
## 2. A near-threshold $\omega J/\psi$ mass enhancement in $B \rightarrow K\omega J/\psi$ decays

At the  $\Upsilon(4S)$ ,  $B\bar{B}$  meson pairs are produced with no accompanying particles. As a result, each  $B$  meson has a total cms energy that is equal to  $E_{\text{beam}}$ , the cms beam energy. We identify  $B$  mesons using the beam-constrained  $B$ -meson mass  $M_{\text{bc}} = \sqrt{E_{\text{beam}}^2 - p_B^2}$  and the energy difference  $\Delta E = E_{\text{beam}} - E_B$ , where  $p_B$  is the vector sum of the cms momenta of the  $B$  meson decay products and  $E_B$  is their cms energy sum. For the final states discussed here, the experimental resolutions for  $M_{\text{bc}}$  and  $\Delta E$  are approximately 3 MeV and 13 MeV, respectively.

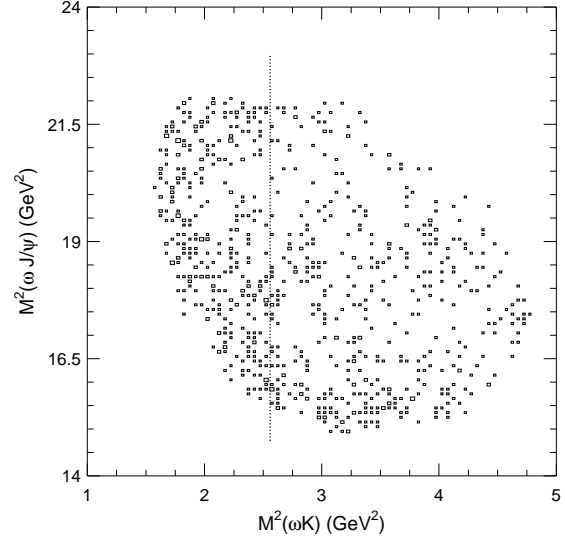
We select  $B \rightarrow K\pi^+\pi^-\pi^0 J/\psi$  candidate events ( $J/\psi \rightarrow \ell^+\ell^-$ ) track combinations with  $M_{\text{bc}}$  and  $\Delta E$  values that are within  $2.5\sigma$  of their nominal values. Figure 1 shows a scatterplot of  $M(\pi^+\pi^-\pi^0 J/\psi)$  (vertical) *versus*  $M(\pi^+\pi^-\pi^0)$  for selected events in the  $\Delta E$ - $M_{\text{bc}}$  signal region. Here a distinct vertical band corresponding to  $\omega \rightarrow \pi^+\pi^-\pi^0$  decays is evident near  $M(\pi^+\pi^-\pi^0) = 0.782$  GeV.

We identify three-pion combinations with  $M(\pi^+\pi^-\pi^0)$  within 25 MeV of  $m_\omega$  as  $\omega$  candidates and form the Dalitz plot of  $M^2(\omega J/\psi)$  (vertical) *versus*  $M^2(\omega K)$  (horizontal) shown in Fig. 2. The clustering of events near the left side of the plot corresponds to  $B \rightarrow K_X J/\psi$ ;  $K_X \rightarrow K\omega$  events, where  $K_X$  denotes strange meson resonances such as  $K_1(1270)$ ,  $K_1(1400)$ , and  $K_2^*(1430)$  that are known to decay to  $K\omega$ . There is also a clustering of events with low  $\omega J/\psi$  invariant masses near the bottom of the Dalitz plot. To study these, we suppress  $K_X \rightarrow K\omega$  events by only looking at events in the region  $M(K\omega) > 1.6$  GeV, to the right of the dashed line in Fig. 2.

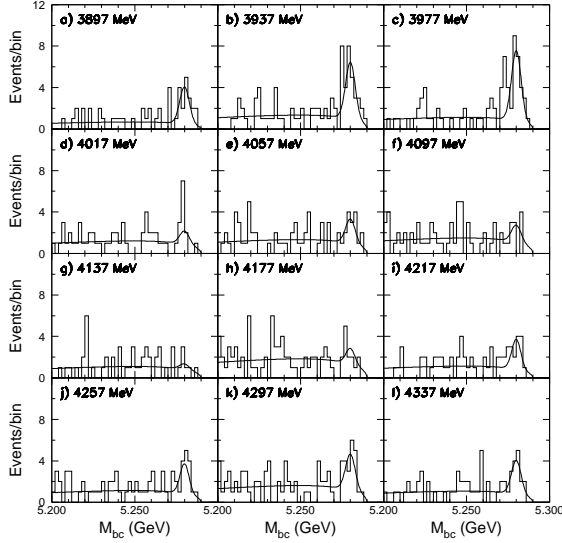
The  $M_{\text{bc}}$  and  $\Delta E$  distributions of the selected events indicate that about half of the entries in the  $M(K\omega) > 1.6$  GeV Dalitz plot region are due to background. To perform a background



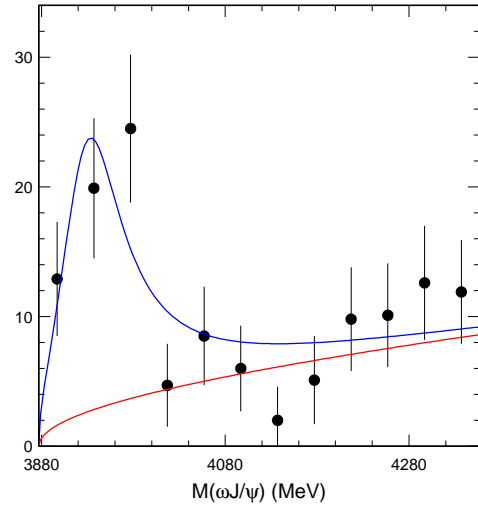
**Figure 1.** A scatterplot of  $M(\pi^+\pi^-\pi^0\ell^+\ell^-)$  (vertical) *versus*  $M(\pi^+\pi^-\pi^0)$  for events in the  $\Delta E$ - $M_{bc}$  signal region. The vertical band indicated by the arrows corresponds to  $\omega \rightarrow \pi^+\pi^-\pi^0$  decays.



**Figure 2.** the Dalitz-plot distribution for  $B \rightarrow K\omega J/\psi$  candidate events.



**Figure 3.**  $M_{bc}$  distributions for events in the  $\Delta E$  signal region for 40 MeV-wide bins in  $M(\omega J/\psi)$ .



**Figure 4.**  $B \rightarrow K\omega J/\psi$  signal yields *vs*  $M(\omega J/\psi)$ . The curve in (a) indicates the result of a fit that uses an  $S$ -wave Breit-Wigner resonance term and a phase-space-like threshold function for the background.

subtraction and determine the level of  $B \rightarrow K\omega J/\psi$  signal events, we separate the data into 40 MeV-wide bins of  $M(\omega J/\psi)$  and measure the  $B$  meson signal levels in the  $M_{bc}$  and  $\Delta E$  distributions. The histograms in Fig. 3 show the  $M_{bc}$  distributions for the twelve lowest  $M(\omega J/\psi)$  mass bins, where strong peaks at  $M_{bc} = m_B$  are evident at low  $\omega J/\psi$  masses, especially for the mass regions covered by Figs. 3(b) and (c). The corresponding  $\Delta E$  distributions (not shown) show similar structure. We establish the  $B \rightarrow K\omega J/\psi$  signal level for each  $M(\omega J/\psi)$  mass bin by performing binned fits simultaneously to the  $M_{bc}$  and  $\Delta E$  distributions with Gaussian functions for the signal and smooth background functions. The smooth curves in Fig. 3 indicate the fitted  $M_{bc}$  curves for each  $\omega J/\psi$  mass bin.

The bin-by-bin signal yields are plotted *vs*  $M(\omega J/\psi)$  in Fig. 4. An enhancement is evident around  $M(\omega J/\psi) = 3940$  MeV. The curve in Fig. 4 is the result of a fit with a  $S$ -wave Breit Wigner function threshold function of the form  $f(M) = A_0 q^*(M)$ , where  $q^*(M)$  is the momentum of the daughter particles in the  $\omega J/\psi$  restframe. This functional form accurately reproduces the threshold behavior of Monte Carlo simulated  $B \rightarrow K\omega J/\psi$  events that are generated uniformly distributed over phase-space.

The fit gives a Breit-Wigner signal yield of  $58 \pm 11$  events with a peak peak mass and total width of

$$\begin{aligned} M &= 3943 \pm 11(\text{stat}) \pm 13(\text{syst}) \text{ MeV} \\ \Gamma &= 87 \pm 22(\text{stat}) \pm 26(\text{syst}) \text{ MeV}, \end{aligned}$$

where the systematic errors are determined from variations in the values when different bin sizes, fitting shapes and selection criteria are used. The event yield translates into a product branching fraction (here we denote the enhancement as  $Y(3940)$ ):

$$\mathcal{B}(B \rightarrow KY(3940))\mathcal{B}(Y(3940) \rightarrow \omega J/\psi) = (7.1 \pm 1.3(\text{stat}) \pm 3.1(\text{syst})) \times 10^{-5},$$

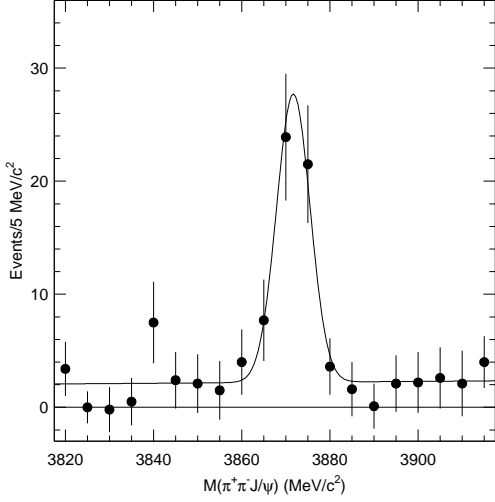
The statistical significance of the signal, determined from  $\sqrt{-2 \ln(\mathcal{L}_0/\mathcal{L}_{\text{max}})}$ , where  $\mathcal{L}_{\text{max}}$  and  $\mathcal{L}_0$  are the likelihood values for the best-fit and for zero-signal-yield, respectively, is  $8.1\sigma$ .

A  $c\bar{c}$  charmonium meson a mass of 3943 MeV would dominantly decay to  $D\bar{D}$  and/or  $D\bar{D}^*$ ; hadronic charmonium transitions should have minuscule branching fractions. On the other hand, decays of  $c\bar{c}$ -*gluon* hybrid charmonium to  $D^{(*)}\bar{D}^{(*)}$  meson pairs are forbidden or suppressed, and the relevant “open charm” threshold is  $m_D + m_{D^{**}} \simeq 4285$  MeV [21, 22], where  $D^{**}$  refers to the  $J^P = (0, 1, 2)^+$  charmed mesons. Thus, a hybrid state with a mass equal to that of the peak we observe would have large branching fractions for decays to  $J/\psi$  or  $\psi'$  plus light hadrons [23]. Moreover, lattice QCD calculations have indicated that partial widths for such decays can be comparable to the width that we measure [24]. However, these calculations predict masses for these states that are between 4300 and 4500 MeV [25], substantially higher than our measured value.

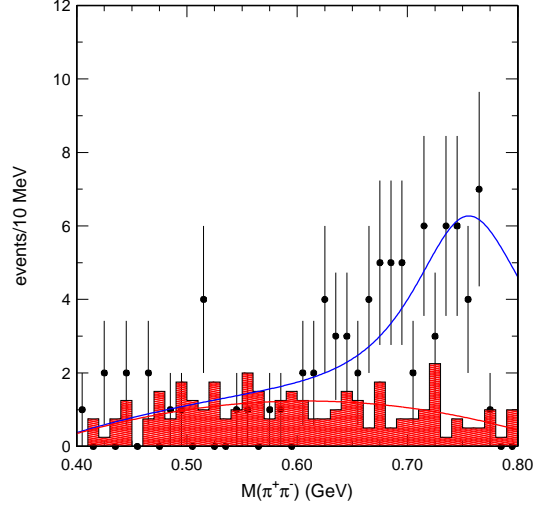
### 3. The $X(3872)$ with $253 \text{ fb}^{-1}$

The  $X(3872)$  was discovered by Belle as a narrow  $\pi^+\pi^-J/\psi$  mass peak in exclusive  $B^- \rightarrow K^-\pi^+\pi^-J/\psi$  decays [4, 26]. Figure 5 shows the  $X(3872)$  signal from a  $253 \text{ fb}^{-1}$  data sample containing 275 million  $B\bar{B}$  pairs. The observed mass and the narrow width are not compatible with expectations for any of the as-yet unobserved charmonium states [27]. Moreover, the  $\pi^+\pi^-$  invariant mass distribution, shown in Fig. 6, peaks near the upper kinematic limit of  $M(\pi^+\pi^-) = 775$  MeV, and has a shape that is consistent with  $\rho \rightarrow \pi^+\pi^-$  decays. Charmonium decays to  $\rho J/\psi$  final states violate isospin and are expected to be suppressed. The  $X(3872)$  and its above-listed properties were confirmed by the BaBar [28], CDF [29] and D0 [30] experiments.

The  $X(3872)$  mass ( $3871.9 \pm 0.5$  MeV [31]) is within errors of the  $D^0\bar{D}^{*0}$  threshold ( $3871.3 \pm 1.0$  MeV [32]); the difference is  $0.6 \pm 1.1$  MeV. This has led to speculation that the  $X$



**Figure 5.** The  $X(3872) \rightarrow \pi^+\pi^-J/\psi$  signal from the  $253 \text{ fb}^{-1}$  data sample.



**Figure 6.**  $M(\pi^+\pi^-)$  for events in the  $X(3872)$  signal peak. The shaded histogram is the sideband-determined background; the curve is the result of a fit with a  $\rho \rightarrow \pi^+\pi^-$  lineshape.

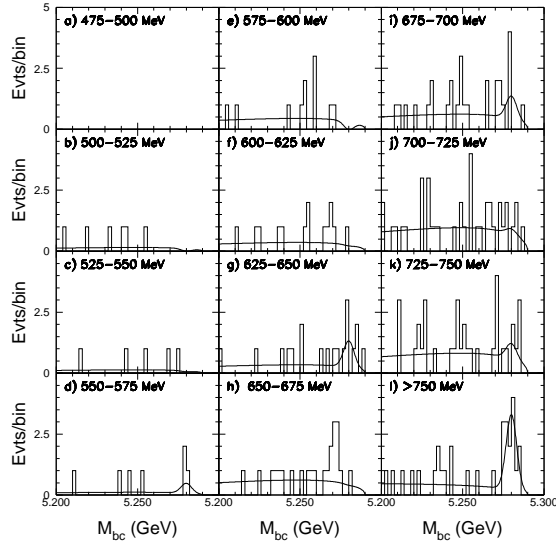
might be a  $D^0\bar{D}^{0*}$  bound state [33, 34, 8]. According to ref. [33], the preferred quantum numbers for such a bound state would be either  $J^{PC} = 0^{-+}$  or  $1^{++}$ . The decay of an  $C = +1$  state to  $\pi^+\pi^-J/\psi$  would proceed via an  $I = 1$   $\rho^0J/\psi$  intermediate state and produce the  $\pi^+\pi^-$  mass spectrum like that we see. In this meson-meson bound state interpretation, the close proximity of the  $X$  mass to  $D^0\bar{D}^{0*}$  threshold compared to the  $D^+D^{*-}-D^0\bar{D}^{0*}$  mass splitting of 8.1 MeV produces a strong isospin violation.

Swanson made a dynamical model for the  $X(3872)$  as a  $D^0\bar{D}^{0*}$  hadronic resonance [34]. In this model,  $J^{PC} = 1^{++}$  is strongly favored and the wave function has, in addition to  $D^0\bar{D}^{0*}$ , an appreciable admixture of  $\omega J/\psi$  plus a small  $\rho J/\psi$  component. The latter produces the  $\pi^+\pi^-J/\psi$  decays that have been observed; the former gives rise to  $\pi^+\pi^-\pi^0J/\psi$  decays via a virtual  $\omega$  that are enhanced because of the large  $\omega J/\psi$  component to the wavefunction. Swanson's model predicts that  $X(3872) \rightarrow \pi^+\pi^-\pi^0J/\psi$  decays should occur at about half the rate for  $\pi^+\pi^-J/\psi$  and with a  $\pi^+\pi^-\pi^0$  invariant mass spectrum that peaks near the upper kinematic boundary of 775 MeV (7.5 MeV below the  $\omega$  peak).

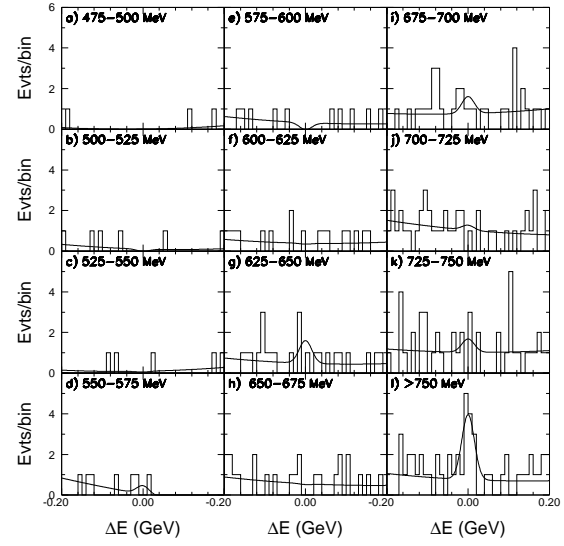
$X(3872) \rightarrow \pi^+\pi^-\pi^0J/\psi$  decays would populate the horizontal band indicated by the horizontal lines in the scatterplot of Fig. 1. This corresponds to the  $\pm 3\sigma$  band  $|M(\pi^+\pi^-\pi^0J/\psi) - m_{X(3872)}| < 16.5 \text{ MeV}$ .

Figure 7 shows the  $M_{bc}$  distributions for events that are in the  $\Delta E$  and  $X \rightarrow \pi^+\pi^-\pi^0J/\psi$  signal regions for 25 MeV-wide  $\pi^+\pi^-\pi^0$  invariant mass bins; Fig. 8 shows the corresponding  $\Delta E$  distributions for events in the  $M_{bc}$  and  $X$  signal regions. There are distinct  $B$  meson signals in both the  $M_{bc}$  and  $\Delta E$  distributions for the  $M(\pi^+\pi^-\pi^0) > 750 \text{ MeV}$  bin and no evident signals for any of the other  $3\pi$  mass bins. The curves in the figures are the results of binned likelihood fits that are applied simultaneously to the  $M_{bc}$  and  $\Delta E$  distributions.

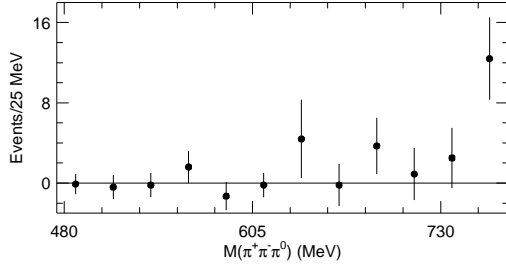
Figure 9 shows the fitted  $B$ -meson signal yields *vs*  $M(\pi^+\pi^-\pi^0)$ . All of the fitted yields are consistent with zero except for the  $M(\pi^+\pi^-\pi^0) > 750 \text{ MeV}$  bin, where the fit gives



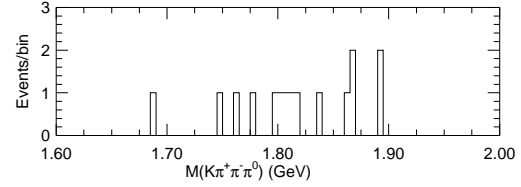
**Figure 7.**  $M_{bc}$  distributions for 25 MeV-wide  $\pi^+\pi^-\pi^0$  invariant mass bins.



**Figure 8.**  $\Delta E$  distributions for 25 MeV-wide  $\pi^+\pi^-\pi^0$  invariant mass bins.



**Figure 9.** The  $B$ -meson signal yields from the fits to the  $M_{bc}$ - $\Delta E$  signals *vs*  $3\pi$  invariant mass.



**Figure 10.** The  $M(K\pi^+\pi^-\pi^0)$  distribution for events in the  $M_X$ - $M(3\pi)$  signal region.

$12.4 \pm 4.1$  events. The statistical significance of the signal in this one bin, determined from  $\sqrt{-2 \ln(\mathcal{L}_0/\mathcal{L}_{\max})}$ , where  $\mathcal{L}_{\max}$  and  $\mathcal{L}_0$  are the likelihood values for the best-fit and for zero-signal-yield, respectively, is  $6.6\sigma$ .

Figure 10 shows the  $M(K\pi^+\pi^-\pi^0)$  distribution for for the  $X \rightarrow \pi^+\pi^-\pi^0 J/\psi$  signal events. The distribution is spread across the limited allowed kinematic region and there is no evident structure that might be producing the high mass peak in Fig. 9 by some sort of a kinematic reflection.

A possible background to the observed signal would be feed-across from the near-threshold  $\omega J/\psi$  enhancement in  $B \rightarrow K\omega J/\psi$  decays described above. Since the  $\omega \rightarrow \pi^+\pi^-\pi^0$  resonance peak is at  $m_\omega = 782.5$  MeV, which is 7.5 MeV above the maximum possible  $3\pi$  invariant mass value for  $X \rightarrow \pi^+\pi^-\pi^0 J/\psi$  decays, there is no overlap between the centroids of the  $\omega J/\psi$  and  $X \rightarrow \pi^+\pi^-\pi^0 J/\psi$  signal bands in Fig. 1. However, there is some overlap in the tails of the kinematically allowed regions for the two processes that might result in some events from one signal feeding into the other.

We determine the level of signal cross-talk to be  $0.75 \pm 0.14$  events from the integral of the fitted function in Fig. 4 over the region of overlap with the  $X(3872)$  signal band. As

an independent check, we refitted for the  $X(3872) \rightarrow \pi^+\pi^-\pi^0 J/\psi$  signal yield with a tighter restriction on  $M(\pi^+\pi^-\pi^0 J/\psi)$ , namely  $m_X - 3\sigma < M(\pi^+\pi^-\pi^0 J/\psi) < m_X + 1\sigma$ , that has *no overlap* with the  $\omega$  band. The  $X \rightarrow \pi^+\pi^-\pi^0 J/\psi$  signal yield in the truncated region is  $10.6 \pm 3.6$  events. For a Gaussian signal distribution with no feed-across background, we expect the truncation of the signal region to reduce the signal by 2.1 events (16%); the observed reduction of 1.8 events is consistent with a feed-across level that is less than one event.

Another possible source of background to the  $X(3872) \rightarrow \pi^+\pi^-\pi^0 J/\psi$  signal are non-resonant  $B^- \rightarrow K^-\pi^+\pi^-\pi^0 J/\psi$  decays. To determine the level of these, we looked for  $B$ -meson signals in the  $M_{bc}-\Delta E$  distributions for events in  $M(\pi^+\pi^-\pi^0 J/\psi)$  sidebands above and below the  $X(3872)$  mass region. There is no evidence for significant signal yields in the  $M_{bc}-\Delta E$  distributions of either sideband. Fits gives an estimate of the non-resonant background in the  $X \rightarrow \pi^+\pi^-\pi^0 J/\psi$  signal bin of  $1.3 \pm 1.0$  events.

To determine the branching fraction, we attribute all of the signal events with  $M(\pi^+\pi^-\pi^0) > 750$  MeV to  $X \rightarrow \pi^+\pi^-\pi^0 J/\psi$  decay. We compute the ratio of  $\pi^+\pi^-\pi^0 J/\psi$  and  $\pi^+\pi^- J/\psi$  branching fractions by comparing this to the number of  $X \rightarrow \pi^+\pi^- J/\psi$  in the same data sample, corrected by MC-determined relative detection efficiencies. The ratio of branching fractions is

$$\frac{\mathcal{B}(X \rightarrow \pi^+\pi^-\pi^0 J/\psi)}{\mathcal{B}(X \rightarrow \pi^+\pi^- J/\psi)} = \frac{N_{ev}(\pi^+\pi^-\pi^0 J/\psi)\varepsilon_{\pi^+\pi^- J/\psi}}{N_{ev}(\pi^+\pi^- J/\psi)\varepsilon_{\pi^+\pi^-\pi^0 J/\psi}} = 1.1 \pm 0.4(\text{stat}) \pm 0.3(\text{syst}), \quad (1)$$

where the systematic error reflects the uncertainty in the relative acceptance, the level of possible feed-across and nonresonant background, and possible event loss due to the  $M(3\pi) > 750$  MeV requirement, all added in quadrature. If we allow for cross-talk and non-resonant contributions at their maximum ( $+1\sigma$ ) values, the statistical significance of the  $X(3872) \rightarrow \pi^+\pi^-\pi^0 J/\psi$  signal is reduced to  $\simeq 4\sigma$ .

#### 4. A new charmonium state in inclusive $e^+e^- \rightarrow J/\psi X$ annihilations.

Some of the biggest surprises from Belle have nothing to do with  $B$ -meson physics at all and have come, instead, from the inclusive  $e^+e^- \rightarrow J/\psi X$  annihilation process. This is demonstrated in Fig. 11, which shows the distribution of masses for systems with more than two charged tracks that recoil against  $J/\psi$  mesons produced in the  $e^+e^-$  continuum at or near the  $\Upsilon(4S)$  resonance. In this figure, which is based on a  $280 \text{ fb}^{-1}$  data sample, the histogram indicates the background level derived from the  $J/\psi \rightarrow \ell^+\ell^-$  mass sidebands.

The prominent peak at  $M_{\text{recoil}} \simeq 2.98$  GeV in Fig. 11 corresponds to the  $\eta_c$ . From the yield of events we determine a cross-section branching-fraction product [15]

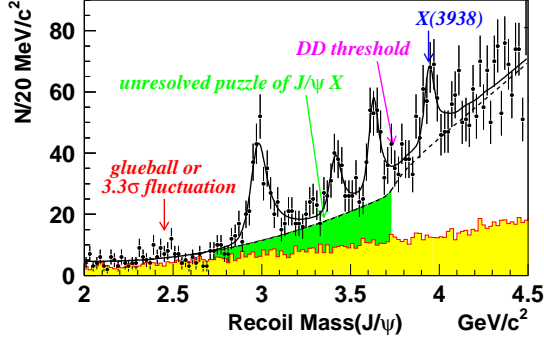
$$\sigma_{\text{Born}}(e^+e^- \rightarrow J/\psi \eta_c) \mathcal{B}(\eta_c \rightarrow > 2 \text{ tracks}) = 25.6 \pm 4.4 \text{ fb.}$$

This is more than an order of magnitude higher than non-relativistic QCD (NRQCD) calculations of  $\sim 2 \text{ fb}^{-1}$  [35]. There is no evident signal for any recoils with mass below  $M_{\eta_c}$ , which is also the  $c\bar{c}$  mass threshold. Also contrary to NRQCD expectations, the four-charmed-quark process  $e^+e^- \rightarrow c\bar{c}c\bar{c}$  dominates inclusive  $J/\psi$  production. From the total number of charmonium states and charmed particles found in the recoil system, we determine the cross section ratio [36]

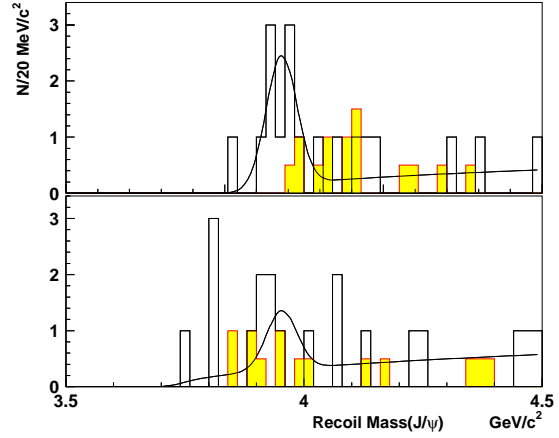
$$\frac{\sigma(e^+e^- \rightarrow J/\psi(c\bar{c}))}{\sigma(e^+e^- \rightarrow J/\psi X)} = 0.82 \pm 0.21;$$

NRQCD predicts this ratio to be  $\sim 0.1$  [37].

The second and third prominent peaks in Fig. 11 are at the masses of the  $\chi_{c0}$  and  $\eta'_c$ , respectively. The fourth peak is well fitted by a Gaussian function with a peak mass of  $3940 \pm 12$  MeV and a signal significance of  $4.5\sigma$ . The width of this state is consistent with



**Figure 11.** The distribution of masses recoiling from the  $J/\psi$  in  $e^+e^- \rightarrow J/\psi X$  annihilations.



**Figure 12.** The  $DD^*$  (top) and  $DD\bar{}$  (bottom) invariant mass distributions for  $e^+e^- \rightarrow J/\psi DD^*$ .

experimental  $M_{\text{recoil}}$  resolution. Since this is rather poor, we can only derive an upper limit on the total width of  $\Gamma < 96$  MeV (90% CL).

We investigated this peak further by studying events where a  $D$  meson is identified in the  $J/\psi$  recoil system, *e.g.* in events of the type  $e^+e^- \rightarrow J/\psi DX$ . Figure 12 shows the distribution of masses recoiling against the  $J/\psi$  for  $e^+e^- \rightarrow J/\psi DX$  events where  $M_X = m_{D^*}$  (top) and  $M_X = m_D$  (bottom). There is an evident  $9.9 \pm 3.3$  event signal for the 3940 MeV state in the  $DD^*$  mass spectrum, with a statistical significance of  $4.5\sigma$ . The signal level is the  $DD\bar{}$  mass spectrum is  $4.1 \pm 2.2$  events with a significance of only  $2.1\sigma$ .

This peak cannot be identified with any known charmonium state. An obvious guess is that it is either the  $\chi'_{c0}$  or the  $\eta''_c$ . However,  $\chi'_{c0} \rightarrow DD^*$  is forbidden and, thus, ruled out. Likewise  $\eta''_c \rightarrow DD\bar{}$  decays are also forbidden, but, since the  $DD\bar{}$  “signal” is ambiguous, we can’t use this to rule out this assignment. On the other hand, an  $\eta''_c$  assignment to the observed peak would imply a  $m_{\psi(3S)} - m_{\eta_c(3S)}$  mass splitting of  $\sim 100$  MeV, about twice as large as the measured splitting for the  $2S$  states. This seems unlikely.

The mass of this fourth peak is very similar to that of the  $\omega J/\psi$  peak seen in  $B \rightarrow K\omega J/\psi$  decays and described above, and a search for it in the  $\omega J/\psi$  decay channel is in progress. In addition, we are examining  $B \rightarrow KDD^*$  decays for a  $DD^*$  component of the  $\omega J/\psi$  enhancement.

## 5. Summary

We observe peaks near 3940 MeV in the  $\omega J/\psi$  mass distribution from  $B \rightarrow K\omega J/\psi$  decays and in the recoil mass spectrum in the inclusive annihilation process  $e^+e^- \rightarrow J/\psi X$ . The latter peak is also seen in the exclusive process  $e^+e^- \rightarrow J/\psi DD^*$  and, thus, cannot be assigned to the  $\chi_{c0}$  charmonium state. At this stage, we cannot tell whether or not the state seen in  $B$  decays and the one seen in inclusive  $J/\psi$  production are one and the same. Further investigation is in progress.

We observe a  $\sim 4\sigma$  signal for  $X(3872) \rightarrow \pi^+\pi^-\pi^0 J/\psi$ . This is the first measurement of an  $X$  decay mode other than  $\pi^+\pi^- J/\psi$ . The  $\pi^+\pi^-\pi^0$  invariant masses are strongly clustered above 750 MeV, near the upper kinematic boundary; this is suggestive of a sub-threshold decay via a virtual  $\omega J/\psi$  intermediate state. Such a decay, at near the measured branching fraction,



was predicted by Swanson based on a model where the  $X(3872)$  is considered to be primarily a  $D^0\bar{D}^{0*}$  hadronic resonance [34].

The presence of the  $X(3872) \rightarrow \omega J/\psi$  decay process would establish the Charge-Conjugation quantum number of the  $X(3872)$  as  $C = +1$ . This, in turn, would mean that the  $\pi^+\pi^-$  system in  $X \rightarrow \pi^+\pi^- J/\psi$  decay comes from the decay of a  $\rho$  meson. The large isospin violation implied by the near equality of the  $\rho J/\psi$  and  $\omega J/\psi$  decay widths is difficult to accommodate in a  $c\bar{c}$  charmonium interpretation of the  $X$ , but a natural consequence of the meson-meson bound state model point of view.

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## References

- [1] T. Nakano *et al.* (LEPS Collaboration), Phys. Rev. Lett. **91**, 012002 (2003). See also K. Hicks, these proceedings.
- [2] B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. Lett. **90**, 242001 (2003) and D. Besson *et al.* (CLEO Collaboration), Phys. Rev. D **68**, 032002 (2003).
- [3] Y. Mikami *et al.* (Belle Collaboration), Phys. Rev. Lett. **92**, 012002 (2003) and P. Krokovny *et al.* (Belle Collaboration), Phys. Rev. Lett. **91**, 262002 (2003). For recent Belle results see A. Drutskoy, these proceedings.
- [4] S.K. Choi *et al.* (Belle Collaboration), Phys. Rev. Lett. **91**, 262001 (2003).
- [5] A. Dzierba, these proceedings; see also A.R. Dzierba *et al.* Phys. Rev. D **69**, 051901 (2003).
- [6] E. Eichten, these proceedings; see also W. Bardeen, E.J. Eichten and C. Hill, Phys. Rev. D **68**, 054024 (2003).
- [7] C. Quigg, these proceedings; see also T. Barnes and S. Godfrey, Phys. Rev. D **69**, 054008 (2004) and E.J. Eichten, K. Lane and C. Quigg, Phys. Rev. D **69**, 094019 (2004).
- [8] See, for example, M.B. Voloshin and L.B. Okun, JETP Lett. **23**, 333 (1976); M. Bander, G.L. Shaw and P. Thomas, Phys. Rev. Lett. **36**, 695 (1977); A. De Rujula, H. Georgi and S.L. Glashow, Phys. Rev. Lett. **38**, 317 (1977); N.A. Törnqvist, Z. Phys. C **61**, 525 (1994); and A.V. Manohar and M.B. Wise, Nucl. Phys. B **339**, 17 (1993).
- [9] D. Horn and J. Mandula, Phys. Rev. D **17**, 898 (1978).
- [10] A. Abashian *et al.* (Belle Collab.), Nucl. Instr. and Meth. A **479**, 117 (2002) and Y. Ushiroda (Belle SVD2 Group), Nucl. Instr. and Meth. A **511**, 6 (2003).
- [11] S. Kurokawa and E. Kikutani, Nucl. Instr. and Meth. A **499**, 1 (2003), and other papers included in this volume.
- [12] S.K. Choi *et al.* (Belle Collaboration), Phys. Rev. Lett. **89**, 102001 (2002).
- [13] K. Abe *et al.* (Belle Collaboration), Phys. Rev. Lett. **89**, 142001 (2002).
- [14] S.K. Choi *et al.* (Belle Collaboration), hep-ex/0408126.
- [15] P. Pakhlov, hep-ex/0412041; see also T. Ziegler, these proceedings.
- [16] T. Lesiak *et al.* (Belle Collaboration), hep-ex/0409065, R. Misuk *et al.* (Belle Collaboration), hep-ex/0412069, and K. Abe *et al.* (Belle Collaboration), Phys. Lett. B **524**, 33 (2002).
- [17] K. Abe *et al.* (Belle Collaboration), hep-ex/0410091 and K. Abe *et al.* (Belle Collaboration), Phys. Rev. D **69**, 112002 (2004).
- [18] H. Nakazawa *et al.* (Belle Collaboration), hep-ex/0412058; K. Abe *et al.* (Belle Collaboration), Eur. Phys. J. C **32**, 323 (2003); and K. Abe *et al.* (Belle Collaboration), Phys. Lett. B **540**, 33 (2002).
- [19] R. Mizuk, talk at PENTA04, Kobe Japan, July 2004, hep-ex/0411005.
- [20] K. Abe, talk at PENTA04, Kobe Japan, July 2004.
- [21] N. Isgur, R. Kokoski and J. Paton Phys. Rev. Lett. **54**, 869 (1985).

- [22] F.E. Close and P.R. Page, Nucl.Phys **B443**, 233 (1995); F.E. Close and P.R. Page, Phys.Lett. **B366**, 323 (1996).
- [23] F.E. Close, Phys. Lett. B **342**, 369 (1995).
- [24] C. McNeile, C. Michael and P. Pennanen (UKQCD Collaboration), Phys. Rev. D **65**, 094505 (2002).
- [25] C. Banner *et al.*, Phys. Rev. D **56**, 7039 (1997); Z.-H. Mei and X.-Q. Luo, Int. J. Mod. Phys. A **18**, 5713 (2003); and X. Liao and T. Manke, hep-lat/0210030.
- [26] The inclusion of charge-conjugate modes is always implied.
- [27] S.L. Olsen, hep-ex/0407033 and K. Abe *et al.* (Belle Collaboration), hep-ex/0408116.
- [28] B. Aubert *et al.* (BaBar Collaboration), hep-ex/0406022.
- [29] D. Acosta *et al.* (CDF-II Collaboration), Phys. Rev. Lett. **93**, 072001 (2004).
- [30] V.M. Abazov *et al.*, (D0 Collaboration), hep-ex/0405004.
- [31] This is the weighted average of all of the reported  $X(3872)$  mass measurements.
- [32] S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B **592**, 1 (2004).
- [33] N.A. Törnqvist, Phys. Lett. B **590**, 209 (2004); F.E. Close and P.R. Page, Phys. Lett. B **578**, 119 (2003); S. Pakvasa and M. Suzuki, Phys. Lett. B **579**, 67 (2004); C.-Y. Wong, Phys. Rev. C **69**, 055202 (2004); and E. Braaten and M. Kusunoki, Phys. Rev. D **69**, 114012 (2004).
- [34] E.S. Swanson, Phys. Lett. B **588**, 189 (2004);
- [35] G.T. Bodwin, J. Lee and E. Braaten, hep-ph/0212181.
- [36] K. Abe *et al.* (Belle Collaboration), BELLE-CONF-0331 (2003).
- [37] P. Cho and A.K. Leibovich, Phys. Rev. D **54**, 6690 (1996); E. Braaten and Yu-Qi Chen, Phys. Rev. Lett. **76**, 730 (1996); V.V. Kiselev, A.K. Likhoded and M.V. Shevlyagin Phys. Lett. B **332**, 411 (1994).